Development of a Primary Standard for the Measurement of Dynamic Pressure and Temperature

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Abstract. The National Institute of Standards and Technology is developing a primary standard for the measurement of dynamic pressure and temperature. Our method requires a dynamic source and a technique for calibrating it. The source is a shock tube; the calibration technique is based on the properties of diatomic gas molecules measured by laser spectroscopic methods.

1. Introduction

At the National Institute of Standards and Technology (NIST), we are developing a primary standard for the simultaneous measurement of dynamic pressure and temperature. This unique facility is to be the basis for dynamic pressure calibration services and will also provide the opportunity to separate pressure and temperature effects in the pressure transducer response. Our method requires a generator of dynamic pressure and temperature, and a technique for measuring them. The generator is a shock tube; the calibration technique is based on the properties of diatomic gas molecules measured by laser spectroscopic methods.

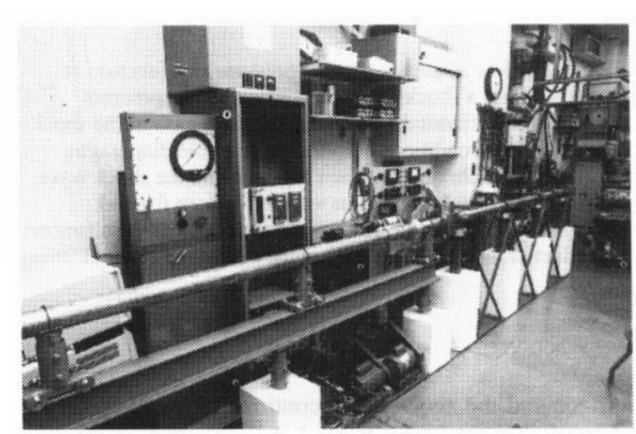

Figure 1. The NIST shock tube.

2. NIST Shock Tube

Figure 1 shows the NIST shock tube. It is a straight tube of uniform cross-section, 63,5 mm in diameter and 7 metres long. A diaphragm divides the tube into two sections, the chamber and the channel. Figures 2a, b, c and d are time-sequence plots of pressure as a function of location within the shock tube and serve to demonstrate how it operates [1-4]. The horizontal axis represents the length of the shock tube; the vertical axis represents pressure.

Figure 2a represents the shock tube in the initial condition where p_4 is the pressure of gas$_4$ in the chamber and p_1 is the pressure of gas$_1$ in the channel. The magnitude of p_4 is greater than that of p_1.

In Figure 2b the diaphragm has been ruptured and gas$_4$ has begun to flow into the channel. The interface between gas$_4$ and gas$_1$ is the contact surface. The pressure behind the contact surface is p_3. The shock wave has formed downstream from the contact surface and is represented by a vertical line signifying the fast rise time of the pressure behind the shock wave p_2. The rise time is of the order of nanoseconds [1, 5, 6] and is considered to be an idealized pressure step generating all frequencies above the low frequency limit. In the chamber, the flow of gas$_4$ results in a rarefaction wave represented by a sloping line signifying that the rarefaction wave is broad because the head of the wave travels faster than the tail.

The rarefaction wave has reflected off the end closure plate of the chamber in Figure 2c while the contact

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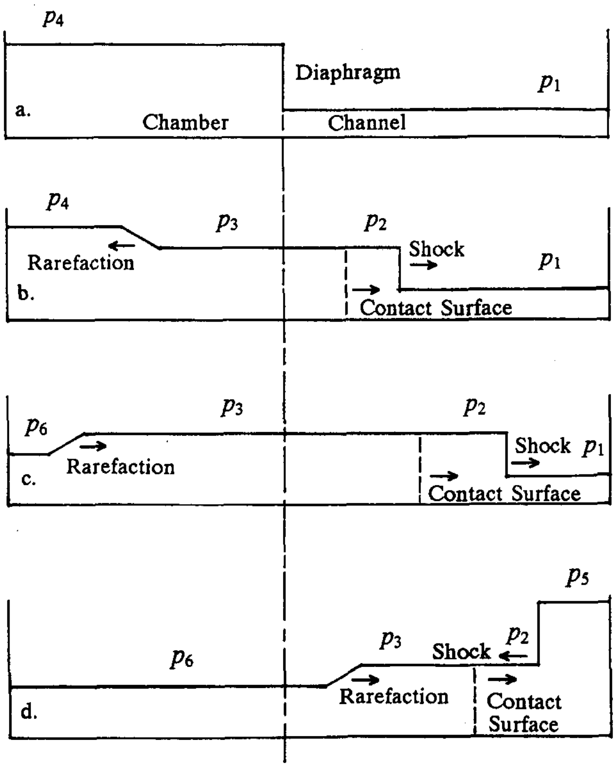

Figure 2. Time sequence plots of pressure as a function of location within a shock tube. The vertical axis represents pressure; the horizontal axis represents the length of the shock tube. (a) initial conditions before rupture of the diaphragm; (b) after the diaphragm has been ruptured and the shock wave, contact surface and rarefaction wave have been formed; (c) reflection of the rarefaction wave at the end of the chamber; (d) reflection of the shock wave at the end of the channel.

surface and the shock wave continue to travel down the channel. The pressure behind the reflected rarefaction wave is p_6. The reflected rarefaction wave is the fastest travelling wave in the shock tube. Its velocity is the sum of the local sound velocity and the flow velocity of gas_4.

In Figure 2d the shock wave has been reflected by the closure plate at the end of the channel. The pressure behind the reflected shock wave is p_5 and is the highest pressure available in the shock tube. For the NIST shock tube, the design maximum for p_5 is 20 MPa.

The magnitude of p_5 just in front of the closure plate remains constant until the arrival at that point of some other disturbance such as the products of the interaction of the reflected shock wave with the contact surface or with the reflected rarefaction wave. This dwell time for p_5 in the NIST shock tube is of order 4 ms when p_5 is 20 MPa. The low frequency limit of the shock tube is the reciprocal of the dwell time [7], which is a few hundred hertz for the NIST tube.

Dynamic pressure calibrations can be extended to very low frequencies by using a quick-opening valve device in conjunction with the shock tube [7]. The proposed NIST quick-opening valve consists of a section of tube 30 mm long mounted to the chamber in place of the channel and closed with the same end-plate as the channel. The volume ratio of the chamber to the 30 mm section is of order 200:1. The chamber is pressurized, the diaphragm is ruptured, and the transducer mounted in the short section or the end-plate experiences a pressure step with a slower rise time than that of the shock tube, but with a dwell time of arbitrary length. The pressure range of the NIST quick-opening valve device will match that of our shock tube, 20 MPa.

Transducers to be calibrated may be mounted either in the side wall or in the closure plate at the end of the channel. Side-wall-mounted transducers experience a slower rise time of the pressure step due to the time required for the shock wave to travel across the active area of the transducer. End-mounted transducers experience the shock wave over the entire active area at the same instant. The diameter of the NIST shock tube is 63,5 mm, which is large enough to mount two transducers side by side in the end-plate for direct comparison. The choice of side-wall mount or end-plate mount for transducer calibration may depend upon the application of the transducers.

Varied pressures and temperatures within the operating range of the shock tube can be generated by varying the initial pressures, the initial temperatures, and the species of gas in the chamber and the channel.

The pressure and temperature generated by the shock tube can be calculated from theory using experimental values of the initial pressures and temperatures, the ratio of the specific heats and the speed of sound for gas_1 and gas_4, and the measured shock speed in the channel. The theory is based on the following assumptions [3]:

(a) The diaphragm is completely and instantaneously removed.
(b) As a result, a plane shock wave is instantly propagated into the channel and a rarefaction wave is instantly propagated into the chamber.
(c) The gas in the channel is compressed adiabatically by the shock wave and has a uniform state with constant thermodynamic quantities of pressure, density, temperature, entropy and flow velocity.
(d) At the same time, the gas in the chamber is expanded isentropically through the rarefaction wave to the same pressure and flow velocity attained by the gas in the channel and the state behind the rarefaction wave is also uniform but with different temperature, density and entropy from the gas behind the shock wave.
(e) These two regions of gas are separated by a mathematically idealized contact surface.

The NIST shock tube has optical access so that the pressures and temperatures generated by the shock tube can be calibrated by the primary standard based on laser spectroscopic techniques. The calibration of this shock tube will thus be independent of the assumptions listed above and free from the uncertainties of shock tube theory.

3. Primary Standard for Dynamic Pressure and Temperature

The primary standard, now under development at the NIST, is based on a sample of diatomic gas molecules whose fundamental properties are used to measure local pressure and temperature [8]. The vibrational frequency of the two atoms along their common axis is a function of pressure. In addition, these molecules have well-defined rotational energy levels whose populations are a function of temperature. We measure these frequencies and populations by means of coherent anti-Stokes Raman spectroscopy (CARS). Since the time required for the CARS measurements can be reduced to nanoseconds, CARS spectra can be obtained from diatomic gas molecules in a dynamic pressure and temperature environment, and the pressure and temperature of that environment can be determined via CARS spectra obtained under known static pressure and temperature conditions or by means of fundamental theory.

The CARS system uses two lasers, called the pump and the Stokes lasers, whose frequency difference is selected to be in resonance with a pure vibrational transition of the diatomic gas. The pump beam is divided into two, and these two beams and the Stokes beam are caused to intersect in the sample space as shown in Figure 3. The volume of the beam intersection defines the sample volume and can be of millimetre by sub-millimetre dimensions. The nonlinear interaction of the electric fields of these laser beams with the diatomic gas molecules generates a third, laser-like beam, called the anti-Stokes beam, which carries the information about the molecular system and, in particular, about its pressure and temperature.

We regard the diatomic gas molecule as the basis for the primary standard because the pressure and temperature dependence of the CARS spectrum can be calculated from first principles. Calculation of the pressure dependence requires knowledge of the intermolecular potentials. For those systems of our particular interest where the intermolecular potentials are not yet adequately known, we will use measured spectra under known static pressure conditions until validated calculations become available.

Our choice of diatomic gas is a few per cent of deuterium in some other host gas. Figure 4 is a plot of a CARS signal plotted as a function of Raman shift for deuterium in nitrogen for four pressures ranging from 5 kPa to 1 MPa. Data obtained in our laboratory are represented by dots; semi-empirical, line-shape theory by the solid lines. First principles calculations are not yet available. The agreement between line-shape theory and measurement is excellent.

Preliminary investigations lead us to believe our uncertainties in the determination of pressure and temperature under transient conditions will be less than 5 % (3 σ).

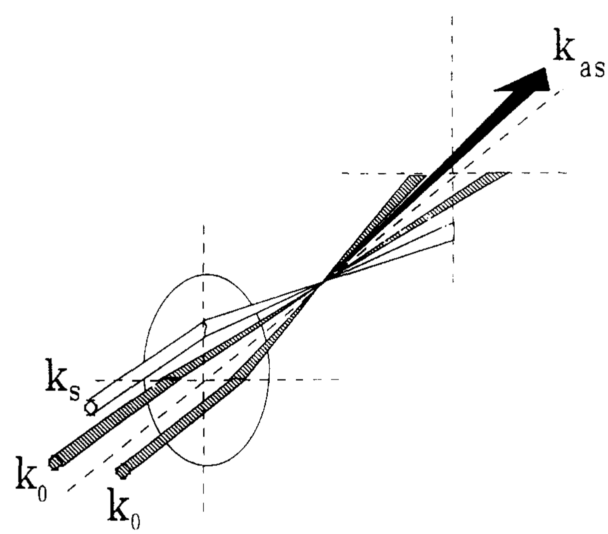

Figure 3. The intersection of laser beams for CARS. Beams k_0 are from the same laser and intersect in the sample space with beam k_s from the second laser. Diatomic gas molecules within the intersection volume interact with the laser beams to produce beam k_{as} which contains the pressure and temperature information for the diatomic gas.

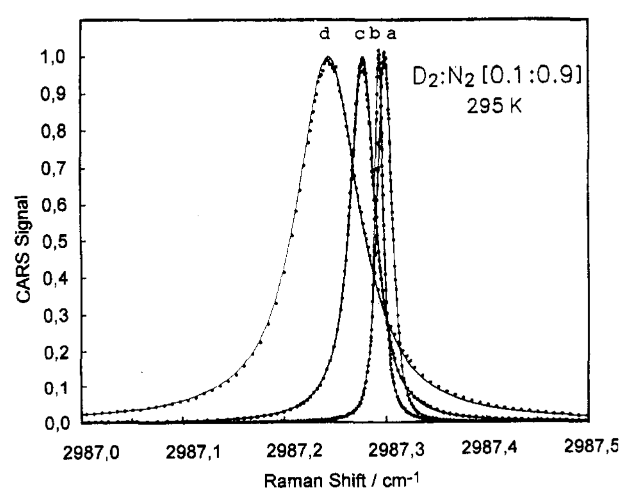

Figure 4. CARS signal plotted as a function of Raman shift for 10 % deuterium in nitrogen at (a) 5 kPa, (b) 0,1 MPa, (c) 0,4 MPa and (d) 1,0 MPa, all at 295 K. The dots are measured points; the solid lines are semi-empirical line-shape theory. Amplitudes have all been normalized to 1.

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